Boussinesq Modeling of Alongshore Swash Zone Currents

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LONG-TERM GOALS

The long-term goal of the study is to develop and integrate numerical models for the understanding and prediction of nearshore processes. The focus of the project is to develop the capability of modeling alongshore swash currents under field conditions based on Boussinesq-type formulations and field observations.

OBJECTIVES

The specific objectives of this project are to:

- Derive a complete set of fully nonlinear Boussinesq-type equations for waves and currents over a permeable beach, including the swash zone.

- Extend the two-dimensional, phase-resolving Boussinesq wave model to the swash zone with an emphasis on alongshore swash motions.

- Integrate the extended model with field data to gain insight into alongshore swash currents, including the correlation between the swash motions and the energetic shear waves, the partitioning of the irrotational (dispersive) and vortical (non-dispersive) motions in the swash zone, and the response of alongshore swash zone currents to the directionality and frequency spreading of offshore wave conditions.

APPROACH

The study involves theoretical formulation, model development and verification, and integration with field observations of swash motions. The starting point of the theoretical formulation is the Euler equation of motion for waves and currents above the permeable seabed and the locally-averaged Navier-Stokes equations for the flow inside the porous layer. A complete set of fully nonlinear Boussinesq-type equations for waves and currents over a permeable beach will be developed. Particular attention will be paid to the conservation property of potential vorticity and poor performance of existing equations when the ratio of the porous layer thickness to the water depth is large. Stokes-type analyses will be carried out to examine the dispersion and damping properties of the new set of equations.

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One of the numerical problems associated with the simulation of swash motions is the requirement of very fine resolution in the swash zone in order to resolve the steep bore front and to prevent numerical instabilities caused by the moving shoreline. A conventional rectangular grid mesh covering a littoral area usually has difficulty to provide enough resolution in the surf and swash zone because of the computational restraint. We will employ the method of transforming the Boussinesq equations derived in a Cartesian coordinate system to the generalized curvilinear coordinates, as shown in Shi et al. (2001), to solve the resolution problem. The transformation allows for varying the grid spacing to give fine enough resolution in the swash zone and avoid over-resolving waves in the deep water. Furthermore, the small grid spacing in the swash zone permits the use of the wetting-drying method on a fixed grid for the treatment of a moving boundary. In addition, a time-dependent transformation of the coordinates will lead to a self-adaptive grid system (a moving grid) suitable for the simulation of swash motions. A comparison of different schemes for the moving boundary in the Boussinesq model will be made to determine the optimum technique with both good accuracy and efficiency for simulating cross-shore and alongshore velocities in the swash zone.

A close collaboration and interaction with field-oriented researchers on swash zone processes is one of the important components of this project. Field data collected by Dr. Britt Raubenheimer's research group at the Woods Hole Oceanographic Institute (WHOI) and Dr. Todd Holland's research group at the Naval Research Laboratory (NRL) will be utilized to verify the Boussinesq model with respect to wave runup and swash motion on beaches. The datasets include in-situ sensor array measurements and video-based observations. The verified Boussinesq model capable of simulating the swash motion on irregular beach topography will become available for the collaborators to study alongshore swash zone currents and allow for the development of hypotheses to be evaluated in future field experiments.

WORK COMPLETED

During the first phase of the project our focus was on the theoretical formulation and analyses. We have derived a new set of Boussinesq-type equations for nonlinear waves and surf-zone currents over a permeable beach, including the swash zone. A Stokes-type analysis has been carried out to examine the fundamental damping and dispersion properties. The vortical properties of the new and pre-existing Boussinesq equations have been carefully investigated. We have documented the results in two manuscripts submitted to journals for possible publication.

RESULTS

Our research work has resulted in a complete set of Boussinesq-type equations suitable for water waves and wave-induced nearshore circulation over an inhomogeneous, permeable seabed. The derivation starts with the conventional expansion of the fluid particle velocity as a polynomial of the vertical coordinate z followed by the depth integration of the vertical components of the Euler equations for the fluid layer and the volume-averaged equations for the porous layer to obtain the pressure field. Inserting the kinematics and pressure field into the Euler and volume-averaged equations on the horizontal plane results in a set of Boussinesq-type momentum equations with vertical vorticity and z-dependent terms. We developed a new approach to eliminating the z-dependency in the Boussinesq-type equations. This technique allows for the existence and advection of the vertical vorticity in the flow field with the accuracy consistent with the level of approximation in the Boussinesq-type equations for the pure wave motion. The complete set of equations is an extension of *Hsiao et al.*' s [2002] equations for nonlinear waves over a porous bed without invoking their assumptions of weak vertical vorticity and weak variation of damping coefficients.

Motivated by the poor performance of pre-existing Boussinesq-type equations when the thickness of the porous layer is several times lager than the water depth, we have examined the scaling of the resistance force and realized the significance of the vertical velocity to the pressure field in the porous layer. This leads to the retention of higher-order terms associated with the damping in the momentum equations. An analysis of the vortical property of the resultant equations indicates that the energy dissipation in the porous layer can serve as a source of vertical vorticity up to the leading order. In comparison with the pre-existing Boussinesq-type equations for both permeable and impermeable bottoms, the complete set of equations improves the accuracy of potential vorticity as well as the damping rate. The equations retain the conservation of potential vorticity up to $O(\mu^2)$, where μ is the measure the frequency dispersion. Such a property is desirable for modeling wave-induced nearshore circulation. Moreover, the procedure of consistently recovering the vertical vorticity and eliminating the *z*-dependency can be used to extend a variety of Boussinesq-type equations originally derived for potential flows to quasi-rotational wave-current motions in the nearshore.

A Stokes-type analysis was carried out to extract the fundamental properties from the complex Boussinesq equations. The linear dispersion relationship and the damping rate owing to the porous layers were compared with the exact solutions for linear waves over a homogeneous, porous, even bottom. We developed a new optimization technique to determine the two model parameters for the new equations.

Figure 1 illustrates the improvement of the complete set of equations in comparison to the existing model. The horizontal axis is the ratio of the water depth to the wave length in the deep water while the vertical axis represents the damping rate over a local wave length. The ratio of the porous layer thickness to the water depth is 10. It is seen in the left panel that the damping rate of the new set of equations agrees very well with the exact solution (solid line). By contrast, the damping rate of the pre-existing equations starts deviating from the exact solution when the relative water depth is greater than 0.04, as shown in the right panel. This demonstrates that the damping property of the new set of Boussinesq-type equations is much better than the pre-existing equations when the thickness of the porous layer is much greater than the local water depth. Because of the improvements in the vortical and damping properties, the new set of Boussinesq-tyep equations will lead to a better numerical model for nonlinear waves and surf-zone currents over permeable beds.

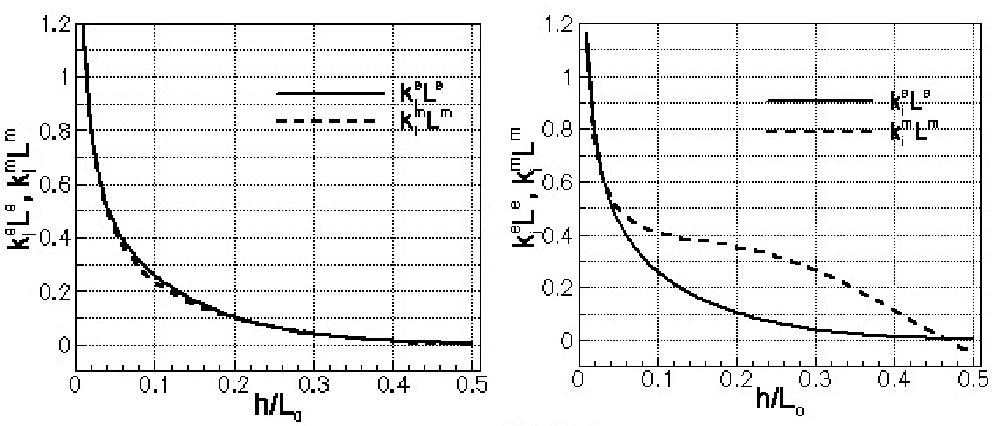

Figure 1. Comparison of the modeled damping rates (dashed lines) with the exact solution (solid lines). The new set of equations (left) is much better than the pre-existing equations (right) when the thickness of the porous layer is much greater than the local water depth.

IMPACT/APPLICATIONS

The proposed research is expected to improve the capability of modeling swash zone processes. First, the study will extend the applicability of Boussinesq models (Chen et al., 1999, and Chen et al., 2003) to the swash zone. This will provide sediment transport models with more realistic estimates of cross-shore and alongshore velocities in the swash zone. Therefore, improvements in predicting sediment transport in the swash zone are anticipated. Second, the complex nature of nearshore processes calls for the integration of numerical models with field measurements in our research. The extended model will become available for Dr. Raubenheimer at the WHOI and Dr. Holland at the NRL as well as their research groups to complement their field study of swash zone processes, including alongshore swash zone currents measured in the NCEX. In addition, it is anticipated that the proposed project will also complement the ongoing NOPP project led by Dr. Jim Kirby to develop and verify a community model for nearshore processes. The phase-resolving Boussinesq model with extension to the swash zone will provide the phase-averaged wave and current models being developed in the NOPP project with useful information about the swash motion and the shoreline boundary conditions. The results will give new insight into alongshore swash zone currents.

TRANSITIONS

The complete set of Boussinesq equations for nonlinear waves and surf zone currents has been shared with the NOPP researchers. As a result, the second-order vertical component of the vorticity vector on an impermeable bed has been implemented into the Boussinesq wave model, FUNWAVE, at the University of Delaware.

RELATED PROJECTS

Dr. Donald N. Slinn at the University of Florida is leading the study titled "Swash Zone Dynamics: Modeling and Data Analysis" with an emphasis on the cross-shore swash motion.

The field observations of cross-shore and alongshore swash-zone fluid velocities by Dr. Britt Raubenheimer at the WOHI will be utilized to verify our numerical models.

Dr. K. Todd Holland at the NRL is leading the study of nearshore processes on heterogeneous beaches. Integration of our models with his field observations is planned.

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